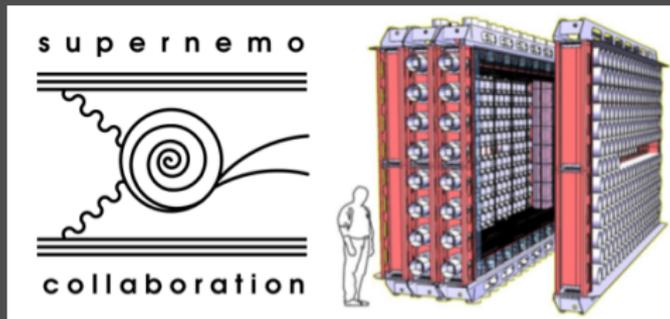


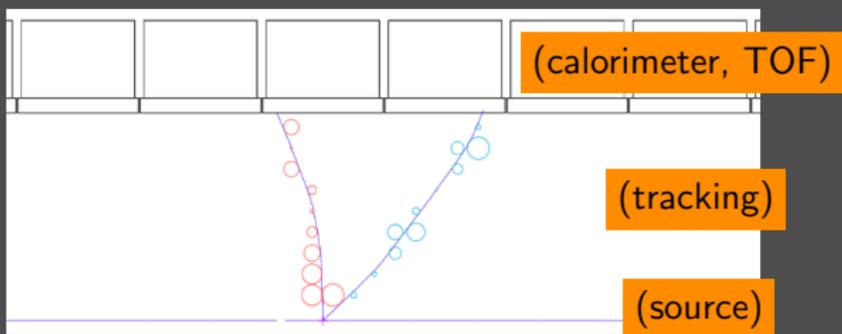
# The SuperNEMO experiment

**Federico Nova**, on behalf of the SuperNEMO Collaboration  
The University of Texas at Austin



# SuperNEMO in a nutshell

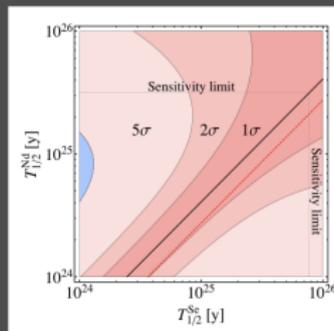
- ▶ physics goals:
  - ▶ primary: neutrinoless double beta decay ( $0\nu 2\beta$ ) of  $^{82}\text{Se}$
  - ▶ other:
    - ▶  $0\nu 2\beta$  of  $^{150}\text{Nd}$  and  $^{48}\text{Ca}$
    - ▶  $2\nu 2\beta$  decays
    - ▶ decays to excited states
    - ▶ Majoron emission
    - ▶ related nuclear physics
- ▶ location: Modane Underground Laboratory (LSM), France, 4800 m.w.e.
- ▶ ~100 collaborators 
- ▶ detector concept:



# SuperNEMO unique features

## 1. multi-isotopes: $^{82}\text{Se}$ , $^{150}\text{Nd}$ , $^{48}\text{Ca}$

comparing the  $T_{1/2}^{0\nu}$  of different isotopes, we can identify the underlying physics (black = mass mechanism, red = right-handed currents)

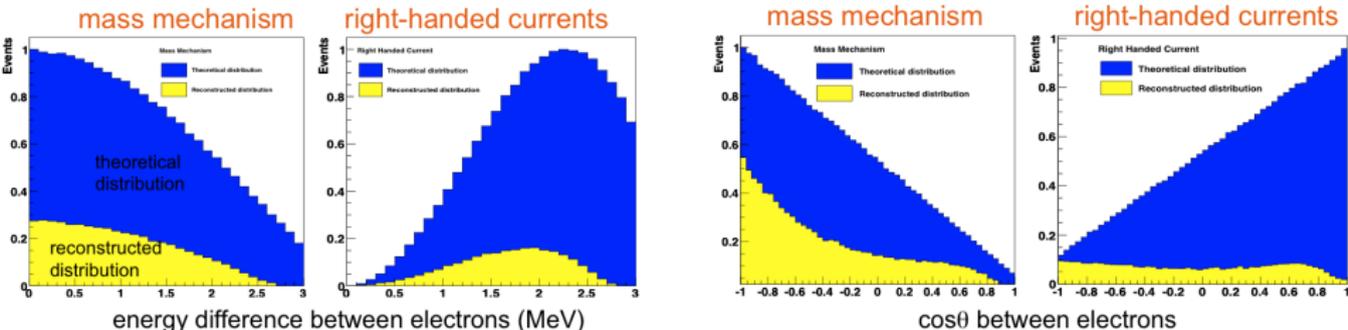


## 2. multi-observables:

- ▶ individual electron energies ( $E_1, E_2$ )
- ▶ times of arrival ( $t_1, t_2$ )
- ▶ curvature in magnetic field ( $\pm$ )
- ▶ common emission vertex
- ▶ angle ( $\cos\theta$ )

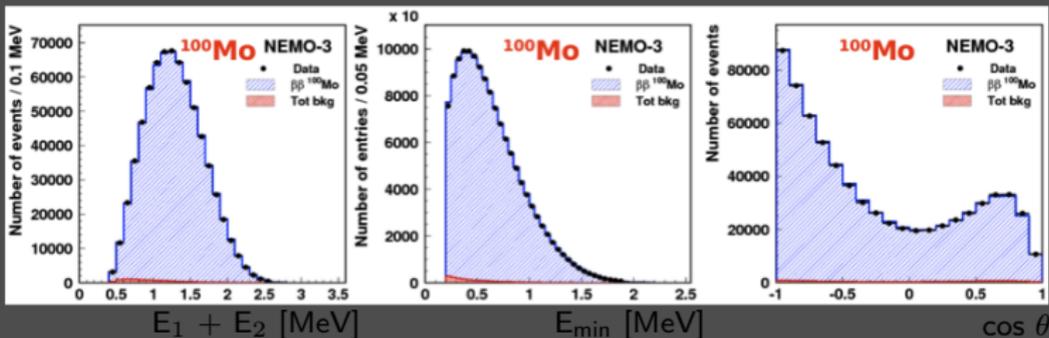
$\implies$

- ▶ full signature of  $0\nu 2\beta$  events
- ▶ powerful background rejection
- ▶ disentangle the  $0\nu 2\beta$  mechanism through topology

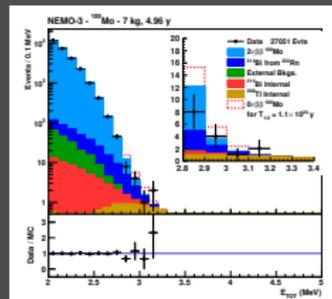
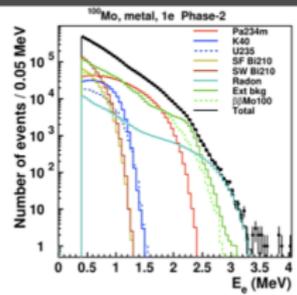
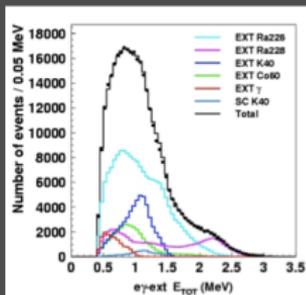


# Our predecessor: the NEMO-3 experiment (2003-2011)

- ▶  $\sim 1$  million  $2\nu 2\beta$  events collected,  $S/B = 76$



- ▶  $T_{1/2}^{2\nu}$  of 7 isotopes with unprecedented precision
- ▶ self-determination of all backgrounds [NIM A 606 (2009) 449–465]



- ▶ neutrino mass limit:  $m_\nu < 0.3 - 0.9$  eV [arXiv 1311.5695]

# From NEMO-3 to SuperNEMO

improve sensitivity parameters:

$$T_{1/2}^{0\nu} \propto \frac{a\epsilon}{m_{\text{mol}}} \times \sqrt{\frac{M \times t}{N_{\text{bkg}} \times \Delta E}}$$

$a$  = isotopic abundance

$\epsilon$  = detection efficiency

$M \times t$  = exposure

$N_{\text{bkg}}$  = background rate  $\left(\frac{\text{cts}}{\text{keV kg y}}\right)$

$\Delta E$  = energy resolution

	NEMO-3	SuperNEMO
mass	6.9 kg	100 kg
isotopes	$^{100}\text{Mo}$ + 6 isotopes	$^{82}\text{Se}$ $^{150}\text{Nd}$ , $^{48}\text{Ca}$
energy resolution (FWHM) @ 3 MeV	8 %	4 %
background	$\sim 100 \mu\text{Bq/kg}$	$\sim 1 \mu\text{Bq/kg}$
sensitivity (90 % CL) $T_{1/2}^{0\nu}$ $\langle m_{\nu} \rangle$	$> 1.1 \times 10^{24} \text{ y}$ $< 0.33 - 0.87 \text{ eV}$	$> 1 \times 10^{26} \text{ y}$ $< 0.04 - 0.10 \text{ eV}$

record breaking background index,  $6 \cdot 10^{-5} \frac{\text{cts}}{\text{keV kg y}}$

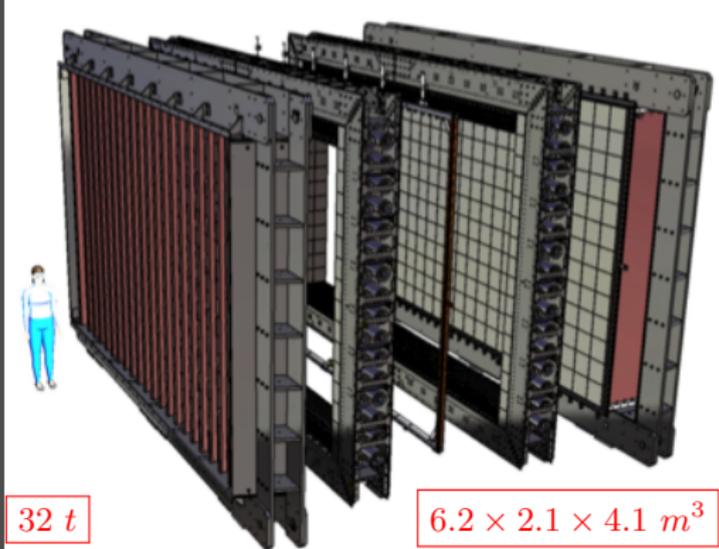
# Demonstrator Module

**source**: 200  $\mu\text{m}$  foil of  $^{82}\text{Se}$  paste with PVA glue on mylar backing film

**tracking**: 2016 drift cells operated in Geiger mode in 25 gauss  $\mathbf{B}$  field

**calorimeter**: 712 scintillator blocks coupled to low radioactivity PMTs

full SuperNEMO: 20 such modules



## Goals

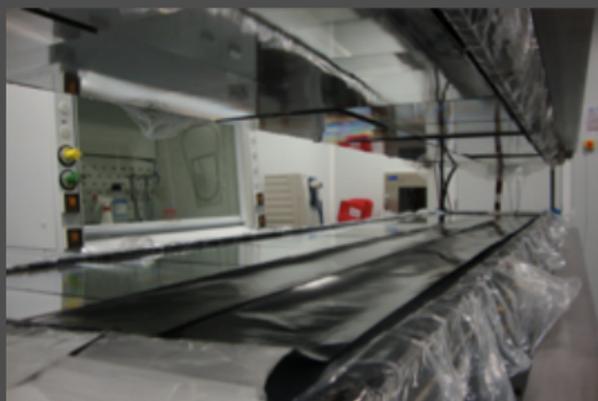
- ▶ commissioning and physics data taking in 2016
- ▶ reach NEMO-3 sensitivity in only 5 months (90 % CL):  
 $\mathcal{T}_{1/2}^{0\nu} > 1.1 \times 10^{24} \text{ y} \rightarrow \langle m_\nu \rangle < 0.33 - 0.87 \text{ eV}$
- ▶ **no background** in the  $0\nu 2\beta$  region in 2.5 years for 7 kg of  $^{82}\text{Se}$
- ▶ sensitivity after 17.5 kg·y exposure (90 % CL):  
 $\mathcal{T}_{1/2}^{0\nu} > 5.7 \times 10^{24} \text{ y} \rightarrow \langle m_\nu \rangle < 0.20 - 0.40 \text{ eV}$

# Status of the Demonstrator construction

- Source
- ▶ already enriched 5.56 kg of  $^{82}\text{Se}$  and 4.56 kg purified (target: 7 kg)
  - ▶ 10% of  $^{82}\text{Se}$  foil produced
  - ▶ foils under measurement since December, only limits so far
  - ▶ R&D proceeds in parallel: very promising “backing film free” solution



enriched  $^{82}\text{Se}$  foil



foil under measurement in BiPo3



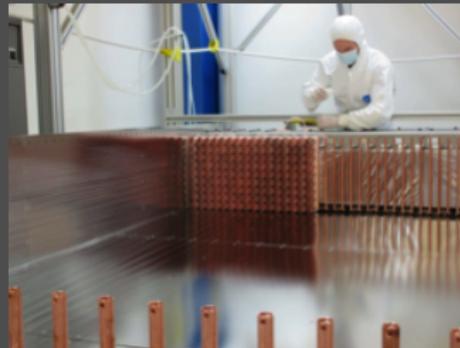
prototype without  
backing film

# Status of the Demonstrator construction

- Tracker
- ▶ automated drift cells production with the wiring robot
  - ▶ first 1/4 tracker "C0" fully assembled and ready for commissioning



wiring robot



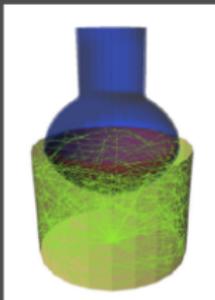
C0 during assembly



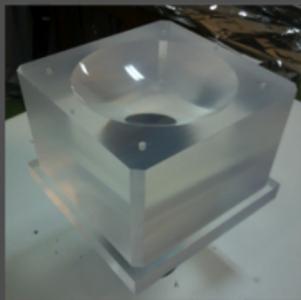
C0 sealed

# Status of the Demonstrator construction

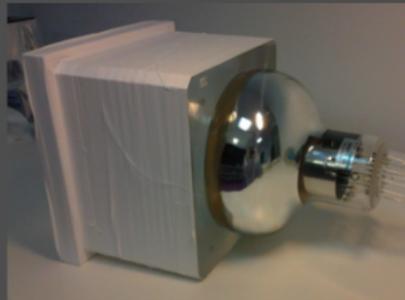
- Calorimeter
- ▶ high QE large 8" PMTs (Hamamatsu R5912) directly coupled to PVT plastic scintillator (no light guide) and improved HV divider
  - ▶ optical modules: 15% produced.
  - ▶ achieved energy resolution of 7 % FWHM @ 1 MeV



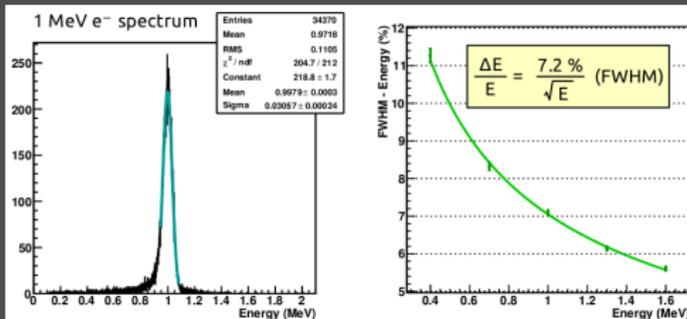
optical simulation



plastic scintillator



optical module



calorimeter resolution (1 MeV beam)

# Reduce the Radon Background to 0.15 mBq/m<sup>3</sup>

- ▶ achieved purification of N<sub>2</sub> to < 20 μBq/m<sup>3</sup>!
- ▶ purification of He to < 5 μBq/m<sup>3</sup> (to be confirmed)



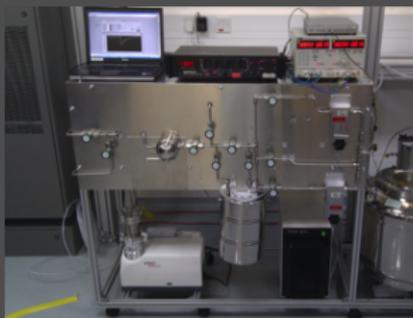
Bordeaux emanation tank



Bratislava emanation setup



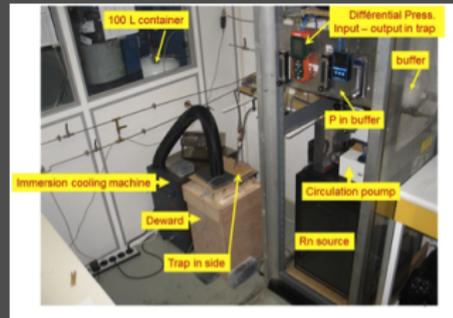
Prague permeability setup



London concentration line



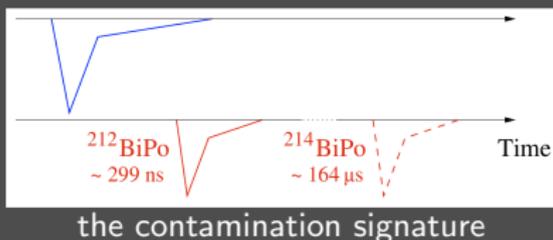
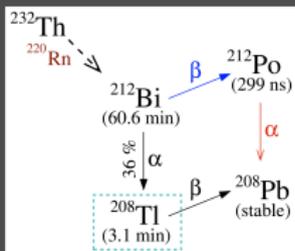
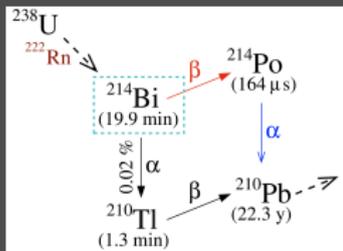
gases purification



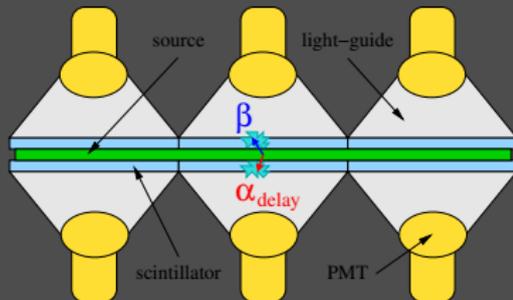
Marseille radon adsorption

# The BiPo3 Detector (LSC, Spain)

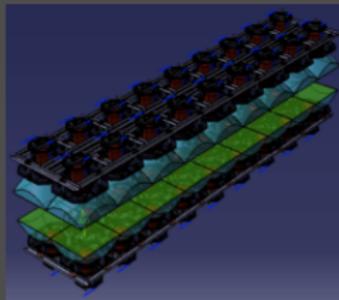
- ▶ dedicated apparatus to measure radiopurity of source foil
- ▶  $^{214}\text{Bi}$  and  $^{208}\text{Tl}$  contaminations identified through **BiPo processes**



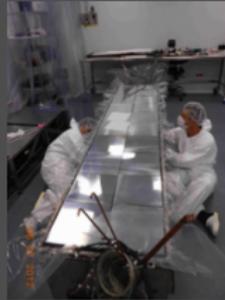
- ▶ 2 mm thick aluminized polystyrene scintillators, PMMA light guides and 5" Hamamatsu low radioactivity PMTs
- ▶ sensitivity:  $^{208}\text{Tl} < 2 \mu\text{Bq/kg}$  and  $^{214}\text{Bi} < 10 \mu\text{Bq/kg}$  in 1 y



BiPo3 detection



detector view



assembly

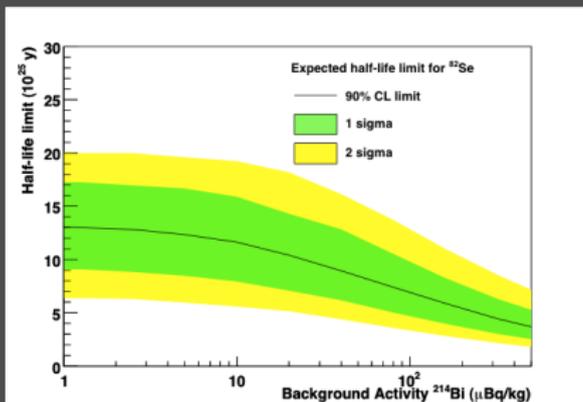
# SuperNEMO timeline and cost range

## ▶ Demonstrator module

- ▶ physics data taking will start in 2016
- ▶ international contribution: \$10M (\$5M capital)
- ▶ US contribution: \$0.8M (NSF)
- ▶ operations cost: 100 k\$/year

## ▶ Full SuperNEMO

- ▶ upgrade with 19 additional modules (2017-2020)
- ▶ reach  $500 \text{ kg} \cdot \text{y}$  exposure in 2025
- ▶ cost range: \$2M / module (capital)



# Backups

# From NEMO-3 to SuperNEMO

	NEMO-3	SuperNEMO
Mass	6.9 kg	100 kg
Isotopes	$^{100}\text{Mo}$ + 6 isotopes	$^{82}\text{Se}$ $^{150}\text{Nd}$ , $^{48}\text{Ca}$
Energy resolution ( $\sigma$   FWHM) @ 3 MeV	3.4   8 %	1.7   4 %
Radon in tracker $A(^{222}\text{Rn})$	5.0 mBq/m <sup>3</sup>	0.15 mBq/m <sup>3</sup>
Sources contaminations $A(^{208}\text{Tl})$ $A(^{214}\text{Bi})$	$\sim 100 \mu\text{Bq/kg}$ 60 - 300 $\mu\text{Bq/kg}$	$< 2 \mu\text{Bq/kg}$ $< 10 \mu\text{Bq/kg}$
Total background cts $\cdot\text{keV}^{-1}\cdot\text{kg}^{-1}\cdot\text{y}^{-1}$	$1.3 \times 10^{-3}$	$6 \times 10^{-5}$
Sensitivity (90 % CL) $\mathcal{T}_{1/2}^{0\nu}$ $\langle m_\nu \rangle$	$> 1.1 \times 10^{24} \text{ y}$ $< 0.33 - 0.87 \text{ eV}$	$> 1 \times 10^{26} \text{ y}$ $< 0.04 - 0.10 \text{ eV}$

# NEMO-3: The Neutrino Ettore Majorana Observatory



- ▶ Located in the *Laboratoire Souterrain de Modane* (LSM) in the French Alps under 4800 m.w.e.
- ▶ Shielded by 30 cm of borated water or wood, 19 cm of steel and radon-free air tent (2004)



Phase 1

Feb. 2003 - Oct. 2004

$$\mathcal{A}_{\text{int}}(^{222}\text{Rn}) \sim 30 \text{ mBq/m}^3$$



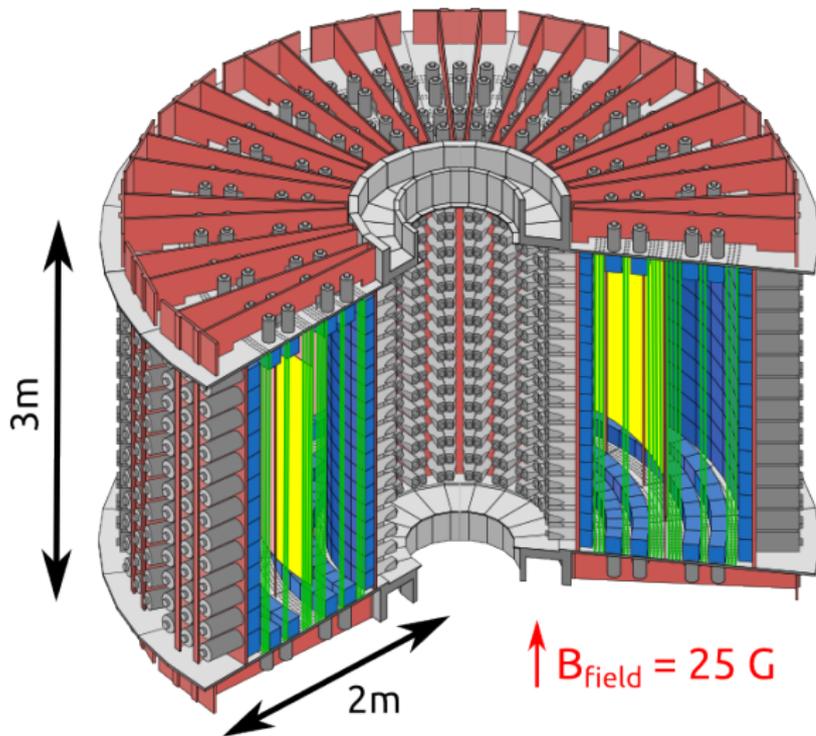
Phase 2

Dec. 2004 - Jan. 2011

$$\mathcal{A}_{\text{int}}(^{222}\text{Rn}) \sim 5 \text{ mBq/m}^3$$

# NEMO-3 Detector

- ▶ NEMO-3 unique tracking and calorimetric double beta decay experiment with 10 kg of sources



## sources

60 mg/cm<sup>2</sup> foils  
10 kg of  $\beta\beta$  isotopes

## tracker

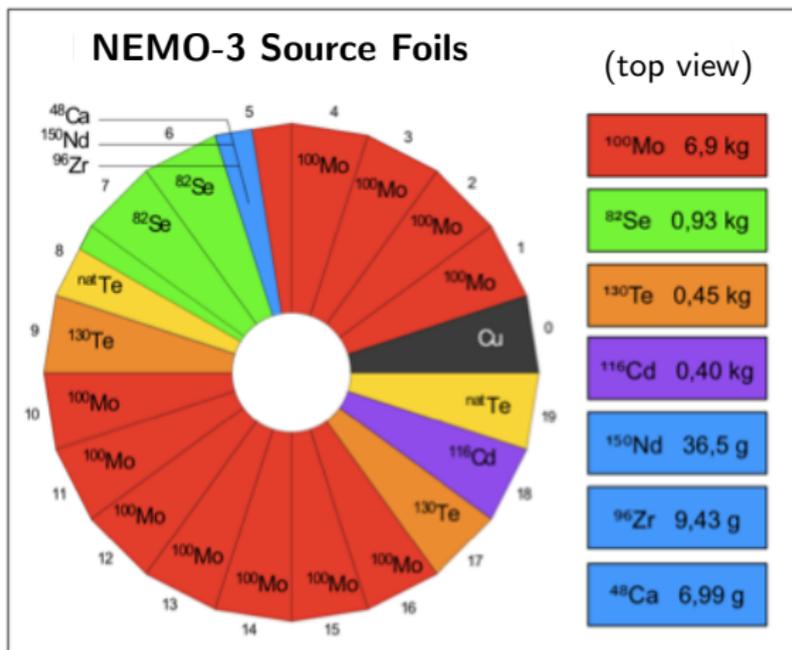
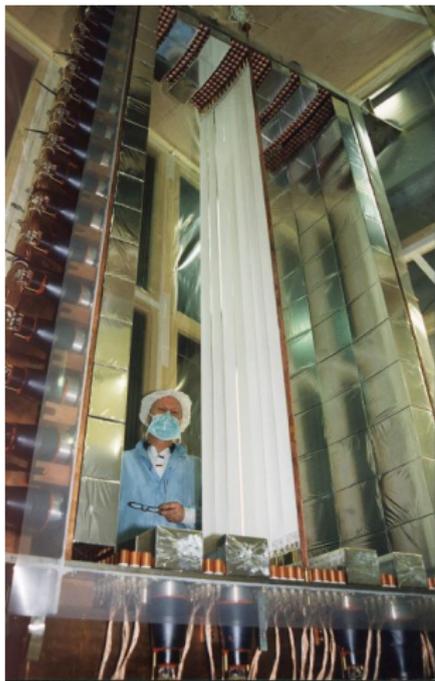
6180 Geiger cells  
vertex resolution :  
 $\sigma_{xy} \sim 3 \text{ mm}$   $\sigma_z \sim 10 \text{ mm}$

## calorimeter

1940 optical modules :  
polystyrene scintillators  
+ 3" and 5" PMTs  
FWHM<sub>E</sub>  $\sim 15\% / \sqrt{E_{\text{MeV}}}$   
 $\sigma_t \sim 250 \text{ ps}$

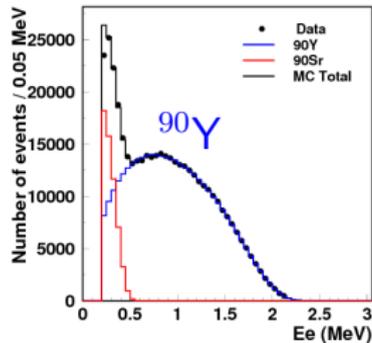
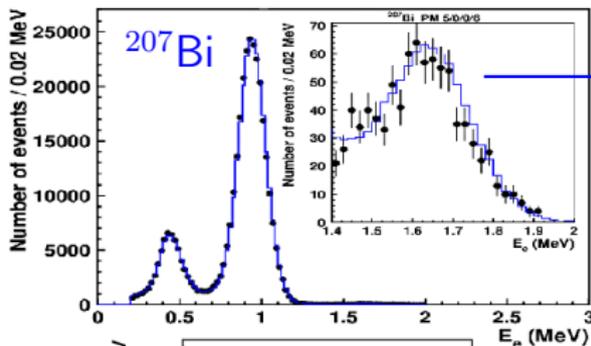
# NEMO-3 Source Foils

- ▶ NEMO-3 is able to study most of the double beta decay isotopes
- ▶ Metallic or composite (glue + isotope powder on mylar) source foils
- ▶ **Blank sources** to check the backgrounds (Cu &  $^{nat}\text{Te}$ )



# NEMO-3 Energy Calibrations

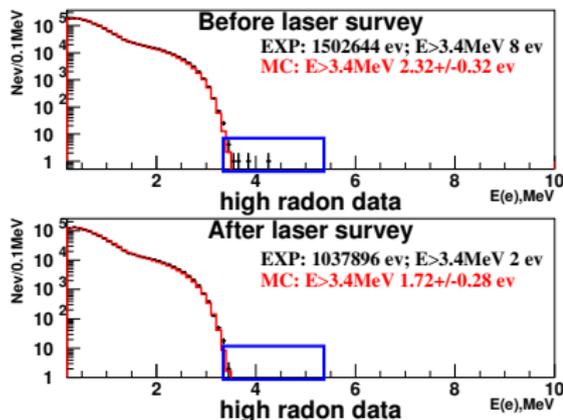
- ▶ 20 calibration tubes close to foils for sources at 3 vertical positions:
  - ▶ reconstruction of the  $1e^-$  events from the source to the calorimeter
  - ▶  $^{207}\text{Bi}$ : 482 and 976 keV conversion electrons every 2-3 weeks
  - ▶  $^{90}\text{Sr}$ - $^{90}\text{Y}$ :  $\beta$ -decay end-point  $Q_\beta = 2280$  MeV
  - ▶  $^{207}\text{Bi}$ : 1682 keV conversion electrons  $\rightarrow$  test the energy scale



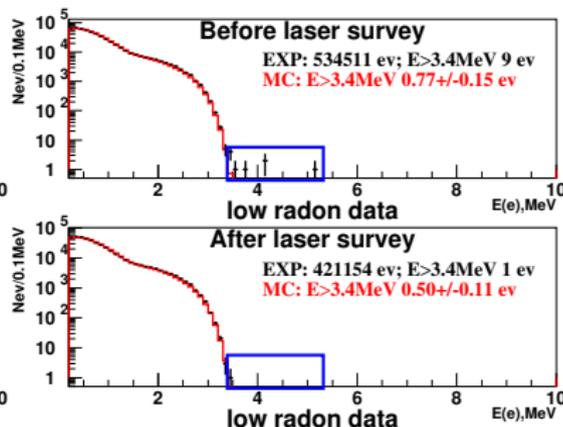
# NEMO-3 Energy Survey

- ▶ Light injection into each calorimeter block through optical fibers:
  - ▶ linearity better than 1 % between 0 and 4 MeV
  - ▶ PMT gain and timing survey twice a day (82 % PMTs < 5 %)
- ▶  $^{214}\text{Bi}$   $\beta$ -decay end-point ( $Q_\beta = 3.27$  MeV) to validate PMT stability:
  - ▶ reconstruction of the BiPo  $e^- \alpha_{\text{delayed}}$  events from radon (background-free channel)

## Phase 1: high radon data



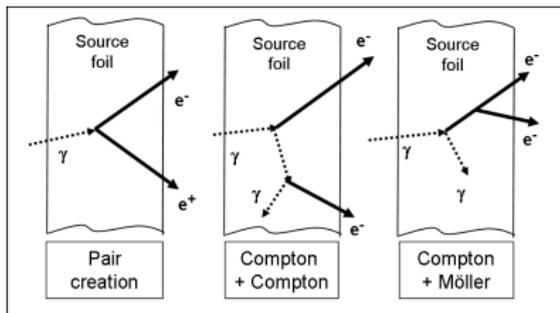
## Phase 2: low radon data



# NEMO-3 Backgrounds

- Natural radioactivity ( $\gamma$ ,  $n$ ) from the detector components or its surroundings and cosmic rays

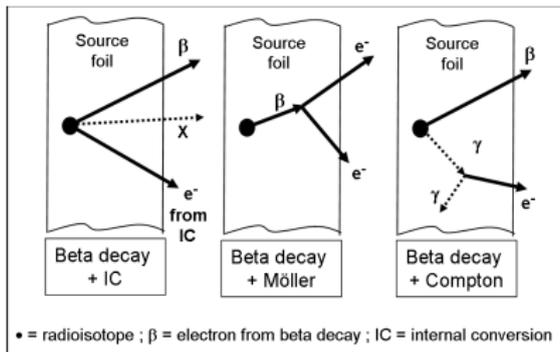
External background



$0\nu 2\beta$ :  
 $^{208}\text{TI}$   $\gamma$  2.6 MeV  
 $(n, \gamma)$  up to  $\sim 10$  MeV

- Radioactive contaminations inside the source foils ( $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ ) or radon daughters deposition on the foils or on the tracking wires

Internal background

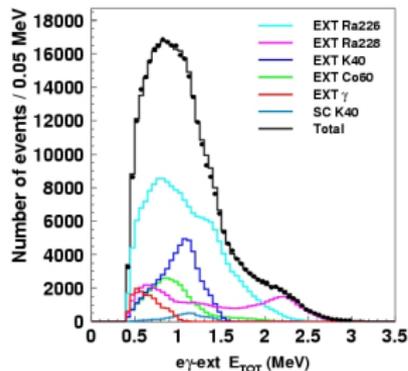
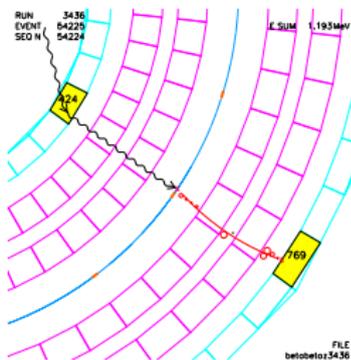


$0\nu 2\beta$ :  
 $^{208}\text{TI}$   $Q_\beta = 5.0$  MeV  
 $^{214}\text{Bi}$   $Q_\beta = 3.27$  MeV

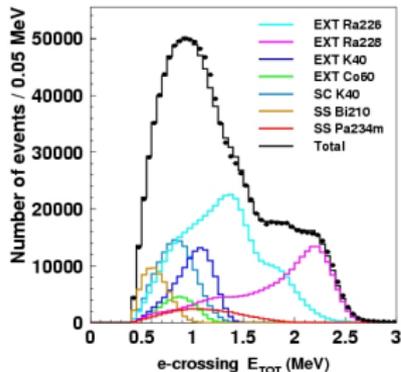
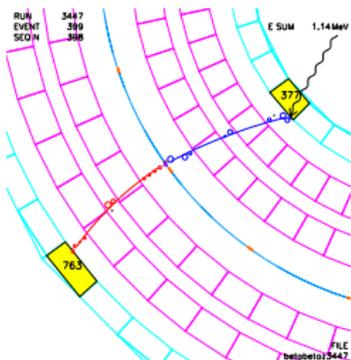
# NEMO-3 External Background Measurements

- ▶ Particle identification:  $e^-$ ,  $e^+$ ,  $\gamma$  and *external TOF*
- ▶ Measurement of all contributions through 2 analysis channels:

$(\gamma e^-)_{\text{ext}}$

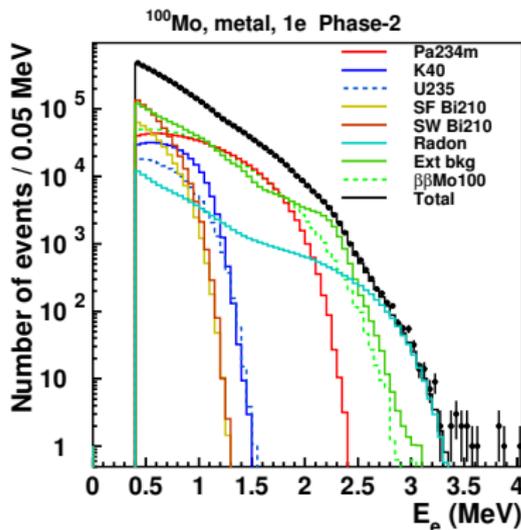
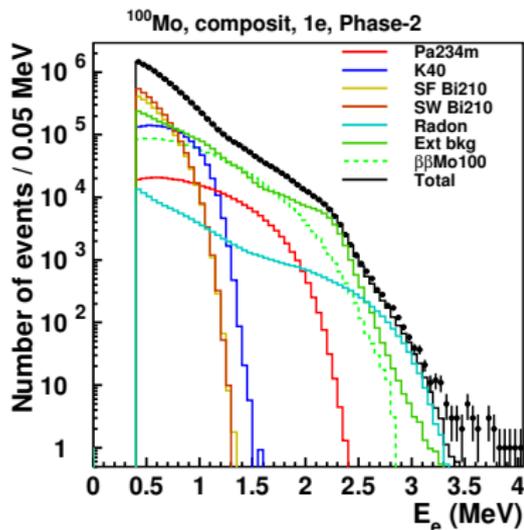


$e^-_{\text{crossing}}$



# NEMO-3 Internal Background Measurements

- ▶ Particle identification:  $e^-$ ,  $e^+$ ,  $\gamma$ ,  $\alpha$  and *internal TOF*
- ▶ Direct measurements through  $e^-$ ,  $e^-N\gamma$  or  $e^-\alpha$  analysis channels
- ▶ Example of fit in the  $e^-$  channel:

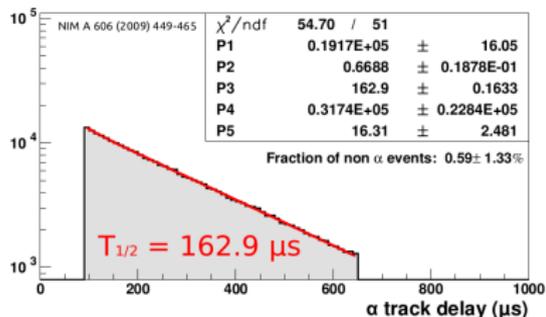
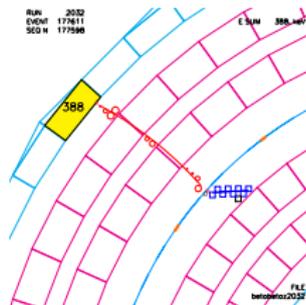
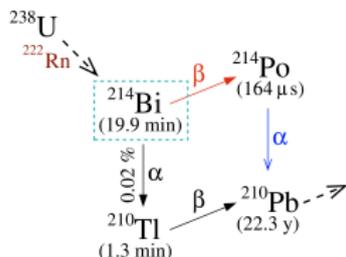


Neutron background not included in these fits (high energy tail)

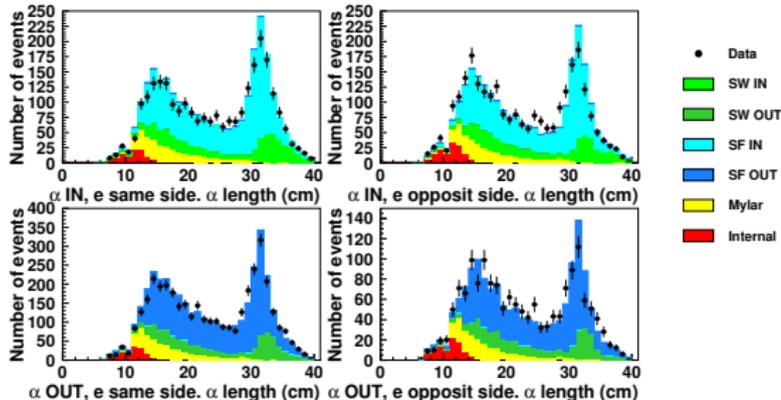
[NIM A 606 (2009) 449–465]

# NEMO-3 Radon and Internal $^{214}\text{Bi}$ Measurements

- Reconstruction of the BiPo  $e^- \alpha_{\text{delayed}}$  events
- $\alpha$  track length and event topology allow to distinguish the origin



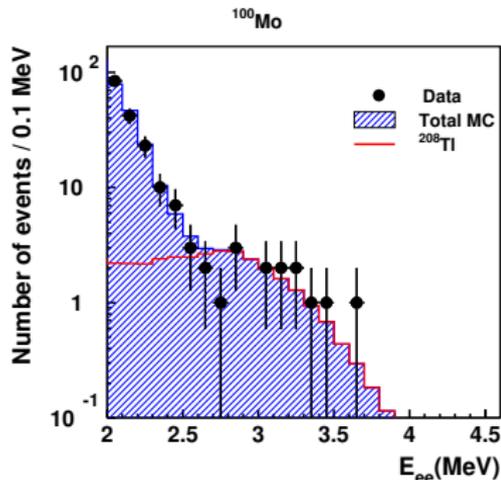
$^{100}\text{Mo}$  composite



# NEMO-3 Checking Internal $^{208}\text{Tl}$ and $^{214}\text{Bi}$ Backgrounds

- ▶  $^{208}\text{Tl}$  activity measurement was checked with two  $^{232}\text{U}$  sources  
→ 10 % systematics compared to HPGe measurement
- ▶  $^{214}\text{Bi}$  activity measurement compared in  $e^- \alpha$  and  $e^- N\gamma$  channels  
→ 10 % systematics
- ▶ Checking these backgrounds in  $2e^- N\gamma$  and  $2e^- \alpha$  channels:

$^{208}\text{Tl}$  in the  $2e^- N\gamma$  channel



$^{214}\text{Bi}$  in the  $2e^- \alpha$  channel  
in [2.8 - 3.2] MeV

Phase 1: 3 events observed  
for  $6.5 \pm 0.4$  expected

Phase 2: 3 events observed  
for  $2.9 \pm 0.2$  expected

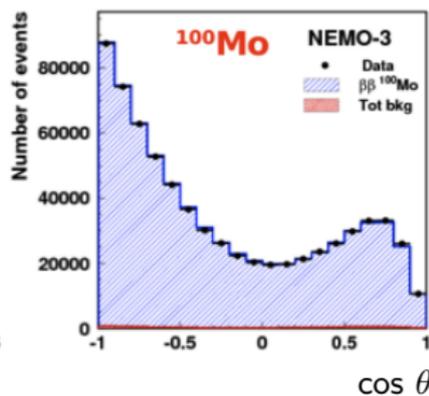
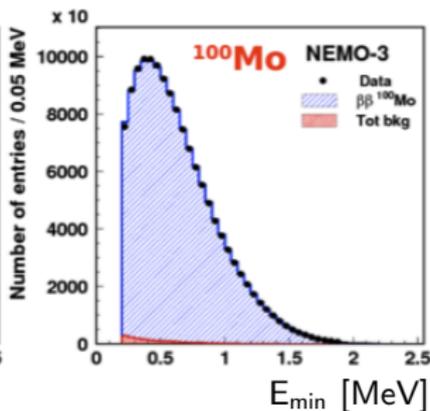
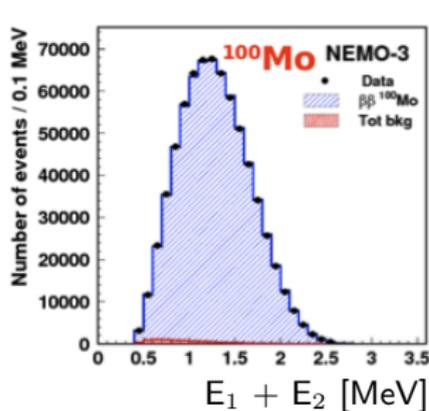
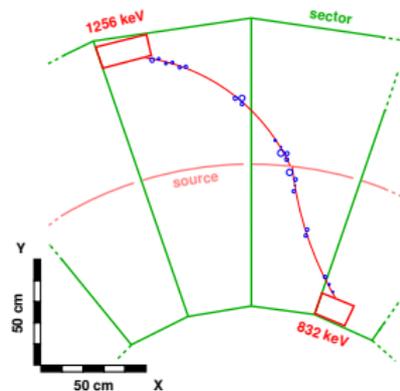
7 events in [2.8 - 3.2] MeV for 8.8 expected

# NEMO-3 $2\nu 2\beta$ of $^{100}\text{Mo}$ Measurement

- ▶ 6.9 kg of  $^{100}\text{Mo}$
- ▶  $\sim 700\,000$   $2\nu 2\beta$  events collected
- ▶ Efficiency  $\mathcal{E}_{2\nu} = 4.3\%$
- ▶ Signal to background ratio  $S/B = 76$
- ▶ Preliminary half-life:

$$\mathcal{T}_{1/2}^{2\nu} = 7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (syst)} 10^{18} \text{ y}$$

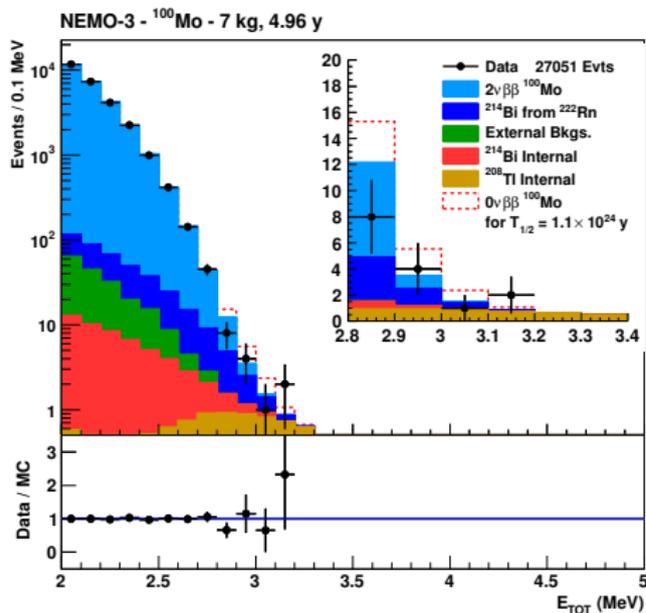
compatible with previously published [Phys. Rev. Lett. 95, 182302 (2005)]



- ▶ 0.7 % systematical uncertainty on the  $2\nu 2\beta$  efficiency above 2 MeV

# NEMO-3 $0\nu 2\beta$ Search with $^{100}\text{Mo}$

- ▶ Detection efficiency  $\mathcal{E}_{0\nu} = 4.7\%$  in the  $[2.8 - 3.2]$  MeV region
- ▶ No event excess observed in  $^{100}\text{Mo}$  after 34.3 kg.y exposure:  
 $\mathcal{T}_{1/2}^{0\nu} > 1.1 \times 10^{24}$  y (90 % CL)



## Expected background in $[2.8 - 3.2]$ MeV

$2\nu 2\beta$	$8.45 \pm 0.05$
$^{214}\text{Bi}$ from radon	$5.2 \pm 0.5$
External	$< 0.2$
$^{214}\text{Bi}$ internal	$1.0 \pm 0.1$
$^{208}\text{Tl}$ internal	$3.3 \pm 0.3$
<b>Total</b>	<b><math>18.0 \pm 0.6</math></b>
<b>Data</b>	<b>15</b>

Total background  
 $1.3 \times 10^{-3}$  cts·keV $^{-1}$ ·kg $^{-1}$ ·y $^{-1}$

[To appear in Phys. Rev. D - [arXiv:1311.5695](https://arxiv.org/abs/1311.5695)]

# NEMO-3 $0\nu 2\beta$ Limits with $^{100}\text{Mo}$

- ▶ Detection efficiency  $\mathcal{E}_{0\nu} = 11.3\%$  in the [2.0 – 3.2] MeV region
- ▶ Modified frequentist analysis [T. Junk, Nucl. Inst. Meth. A 434 (1999) 435]
- ▶ Include statistical and systematic uncertainties and their correlations (background systematics presented above + 7% on the reconstruction efficiency from  $^{207}\text{Bi}$  calibration)

Isotope	Half-life ( $10^{25}$ y) published	$\langle m_\nu \rangle$ (eV) published	$\langle m_\nu \rangle$ (eV) recalculated	$\langle \lambda \rangle$ ( $10^{-6}$ ) published	$\langle \eta \rangle$ ( $10^{-8}$ ) published	$\lambda'_{111}/f$ ( $10^{-2}$ ) published	$\langle g_{ee} \rangle$ ( $10^{-5}$ ) published
$^{100}\text{Mo}$ (this work)	0.11	0.33 - 0.87	0.33 - 0.87	0.9 - 1.3	0.5 - 0.8	4.4 - 6.0	1.6 - 4.1
$^{130}\text{Te}$ (CUORICINO)	0.28	0.31 - 0.71	0.31 - 0.75	1.6 - 2.4	0.9 - 5.3		17 - 33
$^{136}\text{Xe}$ (KamLAND-Zen)	1.9	0.14 - 0.34	0.14 - 0.34				0.8 - 1.6
$^{76}\text{Ge}$ (GERDA)	2.1	0.2 - 0.4	0.26 - 0.62				
$^{76}\text{Ge}$ (HdM)	1.9	0.35	0.27 - 0.65	1.1	0.64		8.1

Using NME from:

J. Suhonen and O. Civitarese, J. Phys. G 39 (2012) 124005

F. Šimković et al., Phys. Rev. C 87 (2013) 045501

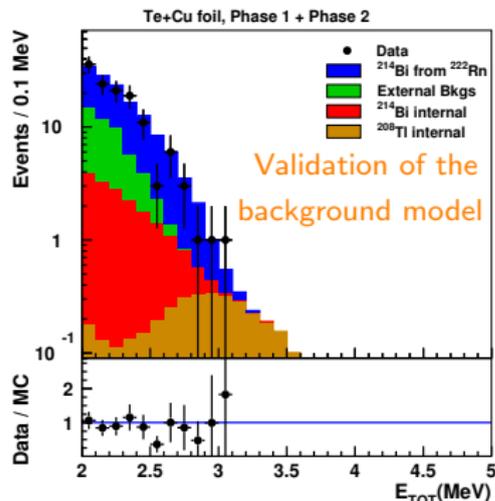
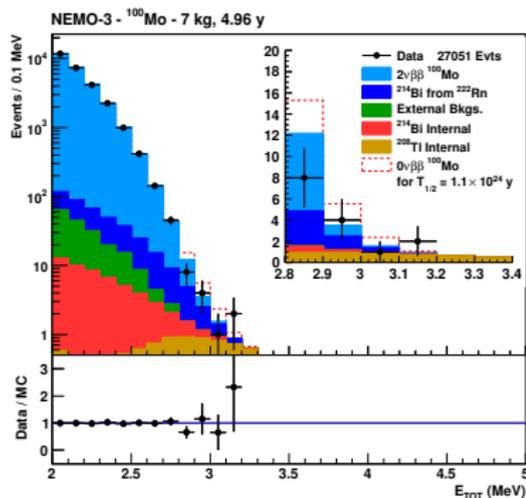
J. Barea et al., Phys. Rev. C 79 (2009) 044301

P. K. Rath et al., Phys. Rev. C 82 (2010) 064310

T.R. Rodriguez and G. Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503

J. Menéndez et al., Nucl. Phys. A 818 (2009) 139

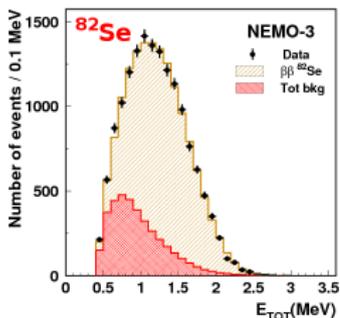
# NEMO-3 High Energy Background



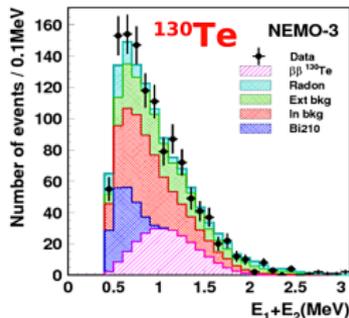
[To appear in Phys. Rev. D - [arXiv:1311.5695](https://arxiv.org/abs/1311.5695)]

- ▶ No events in  $^{100}\text{Mo}$  after 34.3 kg·y exposure above 3.2 MeV
- ▶ No events in copper and natural tellurium samples after 13.5 kg·y exposure above 3.1 MeV
- ▶ Background-free technique for high energy  $Q_{\beta\beta}$  isotopes:  
 $^{48}\text{Ca}$ : 4.272 MeV,  $^{150}\text{Nd}$ : 3.368 MeV or  $^{96}\text{Zr}$ : 3.350 MeV

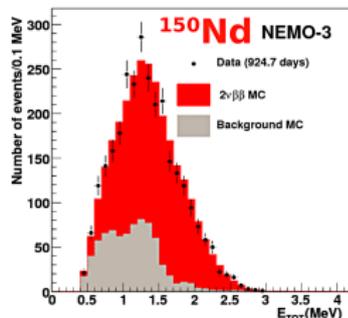
# NEMO-3 $2\nu 2\beta$ Measurement of Lower Mass Isotopes



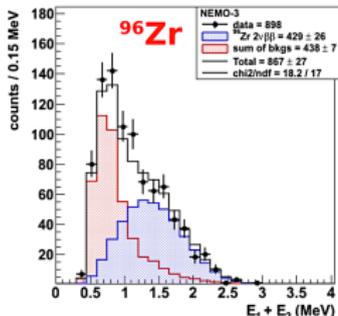
$T_{1/2} = 9.6 \pm 1.0 \cdot 10^{19} \text{ y}$   
PRL 95, 182302 (2005)



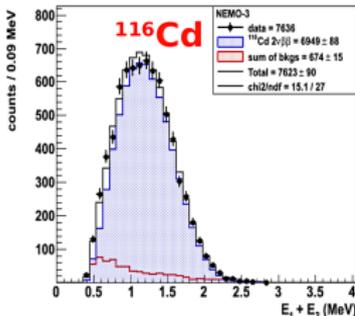
$T_{1/2} = 7.0 \pm 1.4 \cdot 10^{20} \text{ y}$   
PRL 107, 062504 (2011)



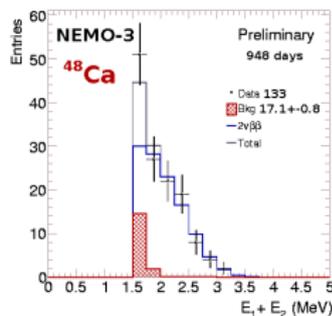
$T_{1/2} = 9.1 \pm 0.7 \cdot 10^{18} \text{ y}$   
Phys. Rev. C 80, 032501 (2009)



$T_{1/2} = 2.35 \pm 0.21 \cdot 10^{19} \text{ y}$   
Nucl. Phys. A 847, 168 (2010)

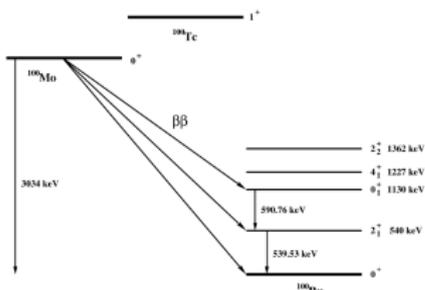


$T_{1/2} = 2.9 \pm 0.3 \cdot 10^{19} \text{ y}$   
To be published



$T_{1/2} = 4.4 \pm 0.6 \cdot 10^{19} \text{ y}$   
Systematics under study

# NEMO-3 Double Beta Decay to Excited States



$2\nu 2\beta$  to excited states of  $^{100}\text{Mo}$ :

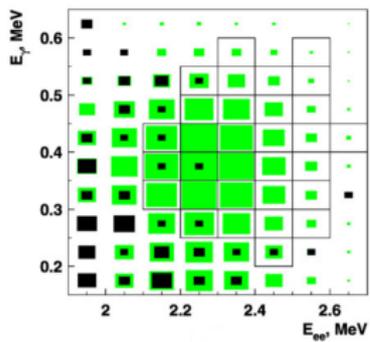
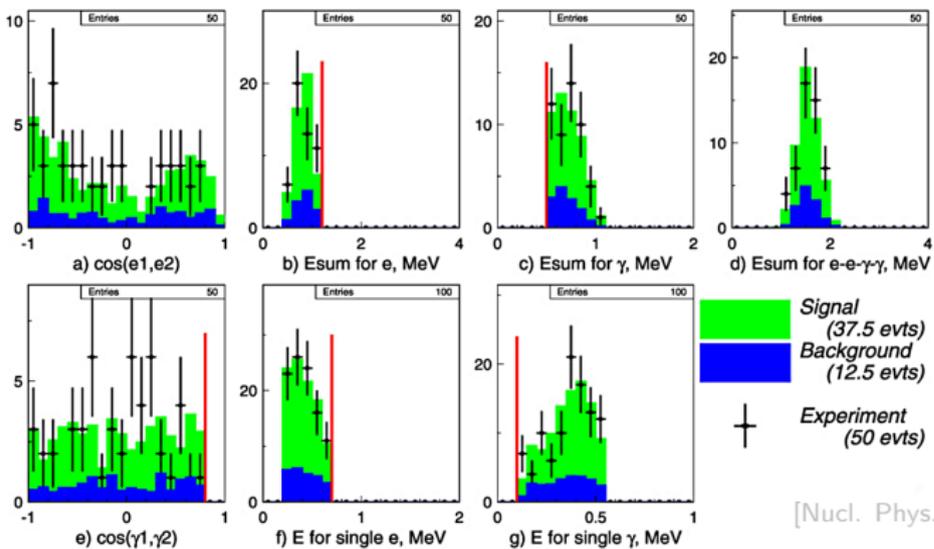
$$\mathcal{T}_{1/2}^{2\nu}(0^+ \rightarrow 0_1^+) = 5.7^{+1.3}_{-0.9} \text{ (stat)} \pm 0.8 \text{ (stat)} 10^{20} \text{ y}$$

$$\mathcal{T}_{1/2}^{2\nu}(0^+ \rightarrow 2_1^+) > 1.1 10^{21} \text{ y @ 90 \% CL}$$

$0\nu 2\beta$  to excited states of  $^{100}\text{Mo}$ :

$$\mathcal{T}_{1/2}^{0\nu}(0^+ \rightarrow 0_1^+) > 8.9 10^{22} \text{ y @ 90 \% CL}$$

$$\mathcal{T}_{1/2}^{0\nu}(0^+ \rightarrow 2_1^+) > 1.6 10^{23} \text{ y @ 90 \% CL}$$



[Nucl. Phys. A 781 (2007) 209-226]

► Other results coming soon on  $^{150}\text{Nd}$  and  $^{96}\text{Zr}$